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Bonded Fibre Reinforced Polymer Strengthening in a Real Fire

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ABSTRACT

FRP strengthening is critically dependent upon the bonding adhesive. The adhesive used is typically an ambient cure epoxy with a glass transition temperature as low as 60ºC. This paper describes the performance of bonded FRP strengthening within real compartment fires (the Dalmarnock Fire Tests), one of which was allowed to grow past flashover. The aim of these real fire tests was to complement the laboratory-based fire tests on FRP strengthened members that are currently being undertaken at various research centres. In this study, externally bonded plate and near-surface-mounted FRP strengthening were applied to the ceiling of a concrete structure. The FRP was protected using either an intumescent coating or gypsum boards, alongside FRP that was left unprotected. The tests demonstrated the vulnerability of FRP strengthening during a real compartment fire. The glass transition temperature was rapidly exceeded in the bonding adhesive for all samples. The near-surface mounted strengthening and the gypsum board protected strengthening was in a visibly better condition after the fire.

KEYWORDS

Fire, testing, epoxy adhesive, CFRP, strengthening, concrete, intumescent, gypsum board.

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1. INTRODUCTION

The popularity of bonded fibre-reinforced polymer (FRP) composite strengthening is largely due to the economy with which it can be applied. Properly designed and installed FRP strengthening often requires less lifting equipment and installation time than other strengthening techniques (such as bonded steel plates or bolted strengthening solutions). To enable easy installation, two-part ambient-cure epoxy resins are usually used to bond the FRP to the existing structure without the need for elevated temperature curing.

Ambient-cure epoxies, however, soften at low glass-transition temperatures (typically 50-65ºC, Concrete Society 2004) and consequently the integrity of the adhesive joint can be lost during a fire. Concerns over the fire performance of bonded FRP strengthening limit their use in buildings, although in many applications the unstrengthened structure will be sufficient to carry the loads acting in the fire limit state and it is deemed acceptable to lose the FRP strengthening during a fire.

A number of research projects around the world have investigated the fire performance of different bonded FRP strengthening systems (Bisby *et. al* 2005). Researchers have also investigated protection systems that might be used to thermally insulate the bonding adhesive from the fire (Barnes and Fidell, 2006; Blondtrock *et al.*, 2001, Williams *et al.*, 2006). The fire performance of FRP, however, has yet to be fully addressed and is a key area requiring further research (Porter & Harries, 2007; ACI 440R-07, 2007). Furthermore, all previous research has been conducted under laboratory conditions using furnaces that follow a standard time-temperature curve such as is prescribed in ISO-834-1 (1999), which can be quite different to the real fire environment (Drysdale, 1998).

In July 2006, the BRE Centre for Fire Safety Engineering at the University of Edinburgh conducted the Dalmarnock Fire Tests (Rein *et al.*, 2007). These tests included real fires within a 23-storey residential building in Dalmarnock, Glasgow, Scotland (Figure 1). The opportunity was taken to include bonded FRP strengthening within two full-scale compartment tests. These are believed to be the first fire tests on FRP strengthening carried out in a 'real' fire, rather than a furnace fire in a laboratory.

2. BONDED FRP STRENGTHENING IN FIRE

Bonded FRP strengthening involves four materials:

- the fibres that reinforce the FRP composite (commonly carbon fibre);
- the matrix polymer that forms the FRP composite (often an epoxy or vinylester resin);
- the bonding adhesive (usually epoxy); and
- the substrate (in this case, concrete).

The FRP composite can either be prefabricated off-site or made in-situ. Prefabrication can be carried out under factory controlled conditions using high performance epoxy or vinylester resin that is cured at elevated temperature and pressure (for example, in an autoclave). The matrix polymer in a prefabricated FRP composite hence has a higher glass transition temperature (around 130ºC, Clarke 1996) than the bonding adhesive (50-65ºC, Concrete Society 2004). The matrix polymer and bonding adhesive are usually the same if the FRP is formed by in-situ wet lay-up techniques.

Typical ambient-cure epoxies for bonding the FRP strengthening to the substrate have a glass transition temperature that is well below the temperatures expected in a compartment fire. Other bonding adhesives have higher glass transition temperatures, but require elevated temperature curing that is difficult to achieve on site and usually uneconomic on a large structure.

The FRP composite usually produces a char layer in fire, which acts as a good insulation layer preventing heat from transferring deep into the composite material. However, the FRP plates used in strengthening concrete structures are thin (typically 1.4mm or less), and the char layer does not form before the adhesive reaches its glass transition temperature (Bisby *et al*., 2005), so that the char layer is therefore not beneficial in this case.

Current practice recognises that the fire performance of bonded FRP can be a concern. For example, UK Concrete Society design guidance states that "*Unless a rigorous analysis is undertaken it is sensible to neglect the strengthening from FRP in fire situations*" (Concrete Society, 2004), and the American ACI design guidance imposes strengthening limits during fire (ACI 440.2R). The loads present during a fire scenario, however, are usually lower than the ultimate load for which the strengthening is designed. The FRP strengthening is often not necessary during a fire, although the strength of the original member should be checked under the fire condition.

Whilst the strengthening provided by the FRP is not needed during fire in many applications, this is unlikely to be the case where FRP strengthening is designed to carry permanent loads. This might occur where strengthening is required to allow the dead load to be increased by high density filing systems, or where FRP is used to carry the perimeter stresses around a new hole cut into a concrete slab to insert services. In such cases, it is logical to specify a suitable protection system that provides thermal insulation and prevents the glass transition temperature of the adhesive being reached. Current guidance highlights the lack of knowledge on suitable protection systems: "*Regulations may require the application of an over-coat layer, which has been tested on the fully-cured composite system*" (Concrete Society, 2004). This is impractical for the design engineer who is working to a limited budget and timescale, and in lieu of properly developed protection systems may be tempted to use 'engineering judgement', adapting traditional insulation methods such as an intumescent coating or gypsum board insulation, possibly based on a simplistic heat transfer calculation.

Recent research has started to address fire protection for bonded FRP. Furnace tests by Blondtrock *et al*. (2001) investigated the performance of FRP plate strengthened concrete slabs, using a variety of gypsum board and mineral wool insulation schemes. Bond between the FRP and the concrete was lost when the adhesive temperature was between 47 and 63ºC, between 24 and 55 minutes into the test depending upon the protection scheme.

Barnes and Fidell (2006) report tests that used a proprietary cementitious fire protection of between 15 and 20mm thickness, and supplemental bolted fastenings. They concluded that this thickness of fire protection was insufficient to keep the adhesive temperature below its glass transition and hence maintain strengthening of the beams. Other proprietary systems have been developed specifically to protect bonded FRP strengthening and these have been tested on columns, beams and slabs (Bisby *et al*. 2005, Williams *et al.* 2006). These tests confirmed that it is difficult to keep the temperature of the adhesive below glass transition, and focused upon the strength of the concrete structure.

3. THE DALMARNOCK FIRE TESTS

The Dalmarnock Fire Tests were conducted within a 23-storey concrete building built in 1964. The building was of cast in-situ construction, with reinforced concrete floor slabs nominally

150mm thick. The bonded FRP strengthening was tested in two real fire compartment tests, Tests 1 and 2, which took place in the living rooms of two identical flats. Figure 2 shows the Test 1 compartment prior to testing, with the FRP strengthening installed on the ceiling. The fire load consisted of office furnishings, arranged so that most of the fuel was towards the east, on the opposite side of the compartment to the window. The furnishings included a two-seat polyurethane sofa (the main fuel source), wooden bookcases and desks, foam padded office chairs, books and papers. The fuel load was estimated to be equivalent to 32 kg/m^2 of wood over the floor area.

A variety of tests (including the bonded FRP strengthening) were conducted within the compartments. The primary aim of Tests 1 and 2 was to demonstrate how the ventilation of a compartment can be used to prevent the fire reaching flashover (Rein *et al*., 2007). Flashover describes the sudden spread of fire throughout a compartment, due to ignition of the fuel and pyrolysed gases by radiation feedback from the smoke layer and the walls of the compartment. A post-flashover fire is accompanied by higher heat fluxes and consequent temperatures. Flashover signifies the transition from a growing fire into a fully-developed fire. It is thus a very important event in the development of a real fire that is not captured by following a time-temperature curve within a furnace that has a very different source of heating and radiative feedback characteristics.

The fire compartment and fire load were identical in Tests 1 and 2, but the ventilation parameters differed. Test 1 was an ‘Uncontrolled Test’, in that no attempt was made to change the ventilation parameters during the fire. The compartment was ventilated by a door open to the rest of the flat, and the openings left by the windows that broke during the later stages of the fire. Test 1 was allowed to grow into a post flashover fire. Test 2, however, was a ‘Controlled Test’, in that the windows and door were opened and closed by remote control. The ventilation parameters during Test 2 were altered to prevent the fire reaching flashover. Consequently, the fire environment experienced by the bonded FRP strengthening was different during the two tests.

4. TEST ARRANGEMENT

Six strips of bonded CFRP strengthening were installed in the compartment used in Test 1 (the ‘Uncontrolled Test’): three 100 x 1.4mm CFRP plates were bonded onto the soffit of the ceiling, towards the west of the compartment and three 12mm diameter near-surface mounted (NSM) CFRP bars were bonded into 20mm wide, 15mm deep grooves cut into the ceiling slab. In Test 2 (the ‘Controlled Test’), a single plate and a single NSM bar were installed. A section through the strengthening is shown schematically in Figure 3.

The FRP strengthening was installed according to standard practice (Concrete Society, 2004) by a contractor who specialises in the application of externally bonded FRP strengthening (Figure 4). The concrete on the underside of the slab was exposed and the surface cleaned prior to strengthening, to ensure good bond, and the grooves cut for the NSM strengthening were similarly prepared. The strengthening works were completed 20 days before the fire test.

Fire protection systems were applied to the bonded FRP strengthening in Test 1 by the University of Edinburgh staff. One of each type of strengthening (externally bonded plate and NSM) was left unprotected, one painted with an intumescent coating, and one protected within a gypsum board box. The location of the strengthening types is shown in Figure 5, and the completed installation is shown in Figure 6. The strengthening in Test 2 was left unprotected.

Intumescent coatings are primarily intended for protecting steel members, not bonded FRP. Their activation temperature (the temperature at which they expand to form an insulating layer) is usually higher than the glass transition temperature of the adhesive. Despite this, the authors are aware that some design engineers have been tempted to use intumescent protection for bonded FRP projects. The opportunity was therefore taken to demonstrate the performance of the intumescent protection during the Dalmarnock tests.

The gypsum board protection used 12mm board to form a box around the strengthening, with two layers of board below the strengthening (Figure 3). The joints in the boards were staggered and the gaps filled with a fire resistant sealant.

Table 1 gives the properties of the strengthening and protection materials used in the Dalmarnock tests. Note in particular that the glass transition temperature of the bonding adhesive is given by the manufacturer as ‘ ≥ 65ºC ’. Adhesive samples were not prepared for glass transition testing at the time of strengthening; however, subsequent tests by the authors (using dynamic mechanical thermal analysis) have given a glass transition temperature of 60ºC after 7 days of curing. The approximate value of glass transition temperature in Table 1 is sufficient for the purpose of the present tests. Note also that the activation temperature of the intumescent was found to be significantly higher than the glass transition temperature of the adhesive, at 120ºC (Liang *et al.*, 2007).

The bonded FRP strengthening in Test 1 was instrumented with thermocouples and strain gauges prior to installation. Thermocouples were loosely attached to the FRP plate or bar at the North, Centre and South positions shown in Figure 5. The thermocouples were thus embedded in the bonding adhesive after installation and they recorded the bondline temperature in the adhesive just above the FRP during the test. The wires were led up through small holes drilled through the concrete slab to data logging equipment in an adjacent flat.

A strain gauge was bonded to the FRP adjacent to each thermocouple, so that the strain gauge readings could be corrected using the manufacturer's temperature calibration chart. The foil strain gauges and gauge adhesive were intended for use up to 200ºC. It was recognised that this temperature would be exceeded and that the strain gauge results would not be reliable thereafter, however practical and time constraints prevented any other type of strain gauge being installed. The strain gauges were expected to give useful data up to 200ºC and qualitative data after this point.

Due to budget and time constraints, the FRP strengthening in Test 2 was not instrumented as it was designed to reach a much lower temperature than in Test 1.

A large quantity of additional instrumentation was used to record the progress of the fire and to monitor the structural response of the slab. Gas temperatures in the fire compartment and just outside the window were instrumented with 270 thermocouples, arranged to record the 3D temperature field. Heat flux gauges and air velocity probes were also used to characterise the fire environment. Temperatures were measured within the ceiling slab by thermocouples embedded in the concrete, and the slab deformation was monitored using deflection gauges placed on the floor above. Strain gauges were also bonded to the top surface of the concrete slab, above the FRP strain gauges. Further details are given in Rein *et al*. (2007).

5. TEST RESULTS AND OBSERVATIONS

5.1 The Fire Environment

Figure 7 shows the Test 1 fire development in terms of the gas phase temperatures measured within the compartment. It shows the mean temperature from the 240 thermocouples that recorded the 3D temperature field within the fire compartment. Two further curves plot the mean temperature plus and the mean minus one standard deviation to indicate the spatial variation in temperatures through the compartment. The ISO-834 time-temperature curve is included as a benchmark against which the experimental results can be compared. Figure 7 shows the three main phases of the fire:

- the growth period, ending with flashover 5 minutes after ignition;
- the fully developed fire, during which the ventilation regime changed at around 13 minutes due to the window breaking, and external flaming which began at 18 minutes;
- the fire was extinguished at 19 minutes by the fire fighters, after which the temperatures decayed.

The peak heat release rate during the fire was 800kW. The heat flux incident upon the ceiling of the compartment at four minutes after ignition is shown in Figure 8. This illustrates the spatial variation in heat fluxes both across the room and across the region of FRP strengthening.

The development of the Test 2 fire was successfully limited by remotely controlling the windows and the door. The temperatures and heat fluxes were lower, and the fire was extinguished by the fire fighters before it reached flashover. Further details of both fires can be found in Rein *et al*. (2007).

5.2 Qualitative Performance of the Bonded FRP Strengthening

Figure 9 shows the condition of the different types of FRP strengthening after the uncontrolled fire (Test 1):

- The unprotected plate (Figure 9a) had completely separated from the concrete. Both the bonding adhesive and the matrix polymer had burnt away, leaving exposed concrete on the ceiling and a bundle of exposed fibres on the floor.
- The intumescent protected plate (Figure 9b) also separated from the concrete, except for a short length at its southern end, where it remained bonded to the concrete. Away from the southern end, the matrix polymer had burnt away to expose the fibres. The bonding adhesive that remained on the ceiling was charred. It should be noted that the gas phase temperatures show a cool region in the south west corner of the room. This is also evident in Figure 8 which shows less heat flux in the south.
- The gypsum-board protection was fully intact after the tests, with no visible holes in the protection or signs that the fire had penetrated it. After the board was removed (Figure 9c), the plate was found to be fully bonded to the concrete, and there was no *visual* damage to either the plate or the adhesive.
- The adhesive around the unprotected NSM bar (Figure 9d) had burnt away, leaving the FRP partially exposed, but the matrix polymer had not burnt away.
- The intumescent coating over the NSM strengthening (Figure 9d) had been activated. The strengthening beneath the intumescent was in place, although the adhesive was glazed and contained thin transverse cracks.
- The gypsum-board protected NSM (Figure 9d) remained intact, and the strengthening beneath was visually unaltered.

In Test 2 (the 'Controlled Fire'), both the unprotected FRP plate and NSM strengthening were *visually* unaffected by the fire: the strengthening and adhesive remained in place, their colour had not changed, and there was no sign of crazing of the adhesive (Figure 9e). The FRP plate was easily removed by hand and the NSM was also removed with some assistance using hand tools. It was not possible to carry out mechanical tests to quantify the post-fire properties of the FRP components or the residual pull-off strength of the bonding adhesive after the fires.

5.3 Quantitative Performance of the Bonded FRP Strengthening

Figure 10 shows the temperatures recorded by the thermocouples in the FRP bondline for each type of strengthening and at each position (north, centre and south). A few thermocouples were inactive, probably due to broken wires. A further 3 thermocouples on NSM bars (gypsum-C, intumescent-N and intumescent-C) gave very low temperatures, and are also believed to have been faulty. The gas phase temperatures included in Figure 10 are from a single thermocouple near the ceiling slab in the centre of the strengthened region, but the wide variation in temperatures across the compartment should be noted (see Figure 7).

In all cases the bondline temperature rapidly exceeded the glass transition temperature of the adhesive. As expected, the bondline temperatures are highest in the unprotected plates, but even with gypsum-board protection, the glass transition temperature was reached less than a minute after flashover. The temperatures in the NSM bonding adhesive are comparable to the temperatures recorded in the plate bondlines, despite the NSM strengthening being embedded within the concrete (Figure 10).

Table 2 lists the times taken at each measurement position to reach 65ºC, the manufacturer's stated minimum glass transition temperature (Table 1). The north position on the unprotected plate exceeded 65ºC before flashover occurred, when the gas phase temperatures were far lower than the ISO-834 curve used in laboratory fire tests (Figure 7). At all other measurement positions with reliable measurements, 65ºC was reached very soon after flashover which occurred at 5 minutes. It is clear here that it took slightly longer for the temperature to reach 65ºC in the NSM strengthening compared with the nearby location in the externally bonded plate (Table 2), because the thermocouples on the NSM strengthening are deeper within the structure.

The rise in bondline temperature is more rapid than observed by previous furnace-based research. Barnes and Fidell (2006), for example, found that the bondline temperature behind an unprotected plate increased gradually to 280ºC after 20 minutes, compared to around 400ºC at the same time in the present tests. Blondtrock *et al*. (2001) found that it took around 20 minutes for the bondline temperature to rise to the glass transition for a gypsum board protection system that was similar (but not identical) to that used in the present tests. Other protection systems (for example, the cementitious coating used by Barnes and Fidell (2001), and the various systems used by Williams et al. (2006)) gave bondline temperatures lower than 100ºC 20 minutes into the test, but it is difficult to make meaningful comparisons between these and the present work.

Furnace-based tests allow the performance of different materials to be compared; however, it must be recognised that they do not properly replicate conditions during a real fire. A furnace does not capture the increased heat release during the flashover event, does not correctly replicate the heat flux (as opposed to temperature) into the component under test, and is based upon a spatial mean temperature.

Figure 11 shows the measured strain gauge results. The strain gauge readings were corrected for temperature effects, based upon the bondline temperatures measured by adjacent thermocouples (Figure 10). The results were corrected to remove:

(a) The apparent strain that would be recorded by the strain gauge as the temperature changes, due to differential thermal expansion of the strain gauge components and electrical effects (based upon the manufacturer's calibration chart, valid up to 200ºC).

(b) Differential thermal expansion between the strain gauge (which had a coefficient of thermal expansion matched to steel) and the CFRP.

(c) The temperature variation of the gauge factor, given by the manufacturer.

The strains plotted in Figure 11 are therefore due to the thermal expansion of the FRP and the mechanical deformation in the FRP due to the fire load applied on the strengthened slab. The poor time resolution for the strain measurements in Figure 11 was a consequence of the very high number of data channels being logged during the test. The very low sampling rate of strain gauge readings by the data logger was unfortunately not anticipated before the test.

Data points for which the allowable operating temperature of the strain gauge (200ºC) has been exceeded are indicated by hollow symbols in Figure 11. The strain gauge adhesive is likely to have softened above this temperature, so any points following these could be inaccurate even though they are shown with solid symbols. Where thermocouple data are not available immediately adjacent to a strain gauge, temperatures were taken from the next position in the same piece of strengthening. The temperature difference between the two locations was estimated by comparing gas phase temperatures, and the resulting uncertainty in the strain is indicated by the shaded regions in the figure.

Despite the limitations of the strain gauge data, they are a useful indication of the performance of the strengthening. Separation of the intumescent painted FRP plate from the concrete, for example, occurred shortly after 10 minutes from the start of the test, but the plate remained in contact at the southern end (as observed in Figure 9b). The gypsum board protected strengthening systems have complete strain traces.

Interpretation of the test results is hampered by the complexity of the fire environment within a real fire. Further analyses are being undertaken to correlate the concrete slab strain with the FRP strain, and consider how the bondline temperatures correlate with the spatial and temporal variations in heat flux. However, the chief aim of these tests was to demonstrate the performance of bonded FRP strengthening within a real fire. It complements the experiments carried out under controlled laboratory conditions, which can be more easily analysed.

6. CONCLUSIONS

The Dalmarnock Fire Tests allowed the performance of plate and NSM bonded FRP strengthening to be investigated in real fires, one of which fully developed post-flashover. The results and preliminary analysis confirm the vulnerability of the bonding adhesive during a fire. The bondline temperature greatly exceeded the glass transition temperature in all tests, even those with thermal protection. Furthermore, this temperature was reached far more quickly than furnace-based testing has suggested.

The unprotected and intumescent protected plate strengthening debonded from the ceiling around 10 minutes after the start of the fire. The test confirmed that the intumescent protection was ineffective due to an inappropriate activation temperature, as was expected prior to the tests. The exposed bonding and matrix adhesive from these two plates burnt away, and would have emitted toxic fumes. The NSM strengthening appeared to have superior fire resistance to the plate strengthening in that it stayed in position and there was far less visible degradation of the bonding adhesive. The surrounding concrete might be expected to draw heat away from the NSM adhesive, but the tests showed that its glass transition temperature was also exceeded. The gypsum board protected the FRP strengthening from visible damage, but again did not prevent the glass transition temperature from being exceeded, which may have affected its ability to strengthen the slab.

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FIGURE CAPTIONS

Figure 1	The Dalmarnock Fire Test in progress (Test 1).
Figure 2	The Test 1 fire compartment, showing the FRP installed on the ceiling.
Figure 3	Types of FRP strengthening and protection (schematic)
Figure 4	Installing a strengthening plate
Figure 5	Schematic plan of the strengthening.
Figure 6	The six strips of FRP strengthening and protection installed in Test 1.
Figure 7	Development of gas phase temperatures in the Test 1 compartment (mean ± 1 standard deviation).
Figure 8	Heat flux incident on the ceiling in the Test 1 compartment (kW/m^2), 4 minutes after ignition.
Figure 9	The condition of the bonded strengthening after the fire.
Figure 10	Bondline temperatures.
Figure 11	FRP strain measurements.

TABLE CAPTIONS

Table 1	Properties of the FRP and protection materials. (Manufacturer’s data sheet values).
Table 2	Time after ignition for bondline temperatures to reach 65ºC.

Table 1: Properties of the FRP and protection materials (manufacturer's data sheet values)

Bonding adhesive	*Two component epoxy based adhesive*	
	Mechanical properties:	E = 10 GPa; Lap shear strength = 17 MPa
	Cure time:	Fully cured in 7 days
	Glass transition temperature:	≥ 65ºC
FRP plate	*Pultruded MM (medium modulus) CFRP plate with epoxy matrix*	
	Dimensions:	100 x 1.4mm
	Mechanical properties:	Tensile modulus = 170 GPa; Tensile strength = 3100 MPa
	Coefficient of linear thermal expansion:	0.6×10^{-6} /ºC
FRP NSM rod	*Pultruded CFRP rod with epoxy matrix (smooth surface)*	
	Dimensions:	12mm diameter
	Mechanical properties:	Tensile modulus = 165 GPa; Tensile strength = 2500 MPa
	Coefficient of linear thermal expansion:	0.6×10^{-6} /ºC
Intumescent paint	*Thin film water borne intumescent coating*	
	Application:	2 coats by brush, estimated thickness 450μm
	Activation temperature	120ºC, from tests on the same material by Liang *et al*. (2007).

Table 2: Time after ignition for bondline temperatures to reach 65ºC

Type of fire protection	Measurement location	Plate strengthening mins:secs	NSM strengthening: mins:secs
Unprotected	North	4:14	5:20
	Centre	-	5:55
	South	5:20	6:25
Intumescent	North	-	-
	Centre	5:01	-
	South	5:25	5:50
Gypsum Board	North	-	5:23
	Centre	5:28	-
	South	-	-

Note: Blanks indicate that no reliable temperature data was available.

Figure 1: The Dalmarnock Fire Test in progress (Test 1).

Figure 2: The Test 1 fire compartment, showing the FRP installed on the ceiling.

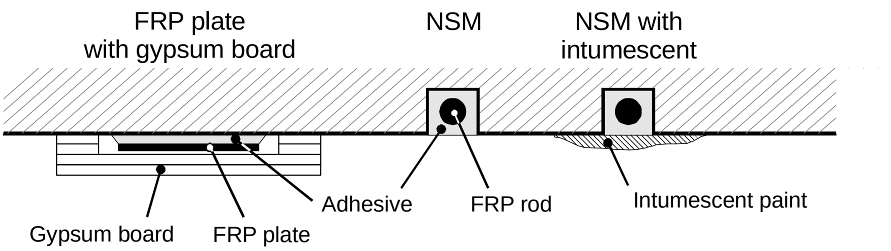

Figure 3: Types of FRP strengthening and protection (schematic)

Figure 4: Installing a strengthening plate

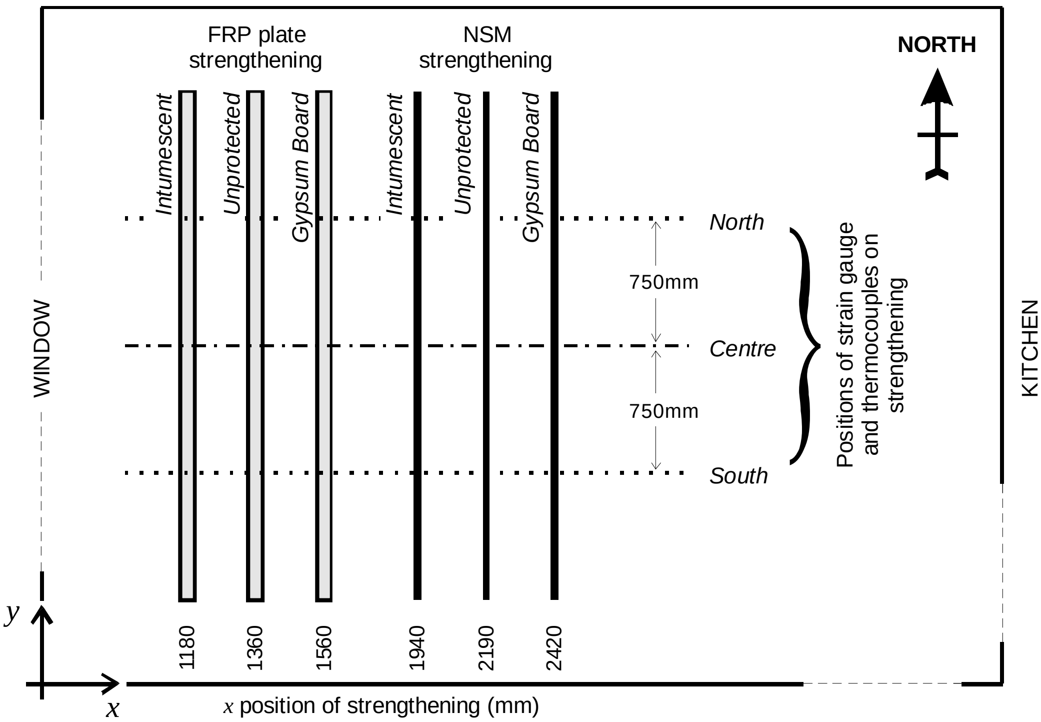

Figure 5: Schematic plan of the strengthening.

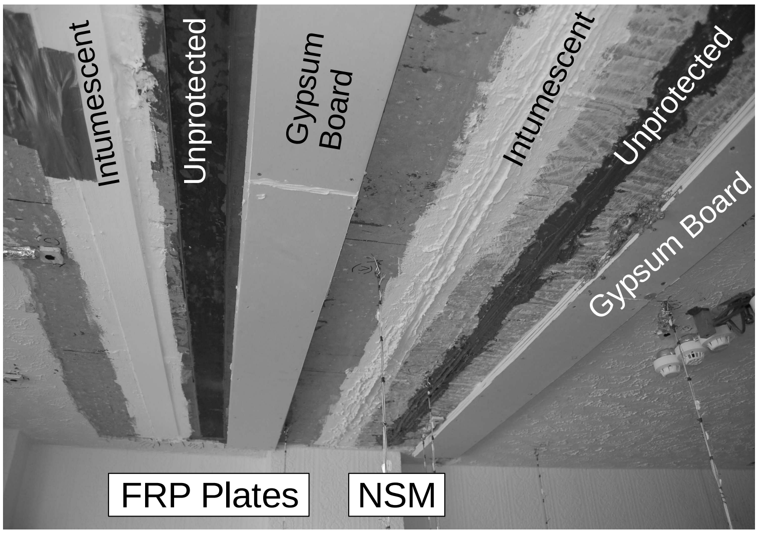

Figure 6: The six strips of FRP strengthening and protection installed in Test 1.

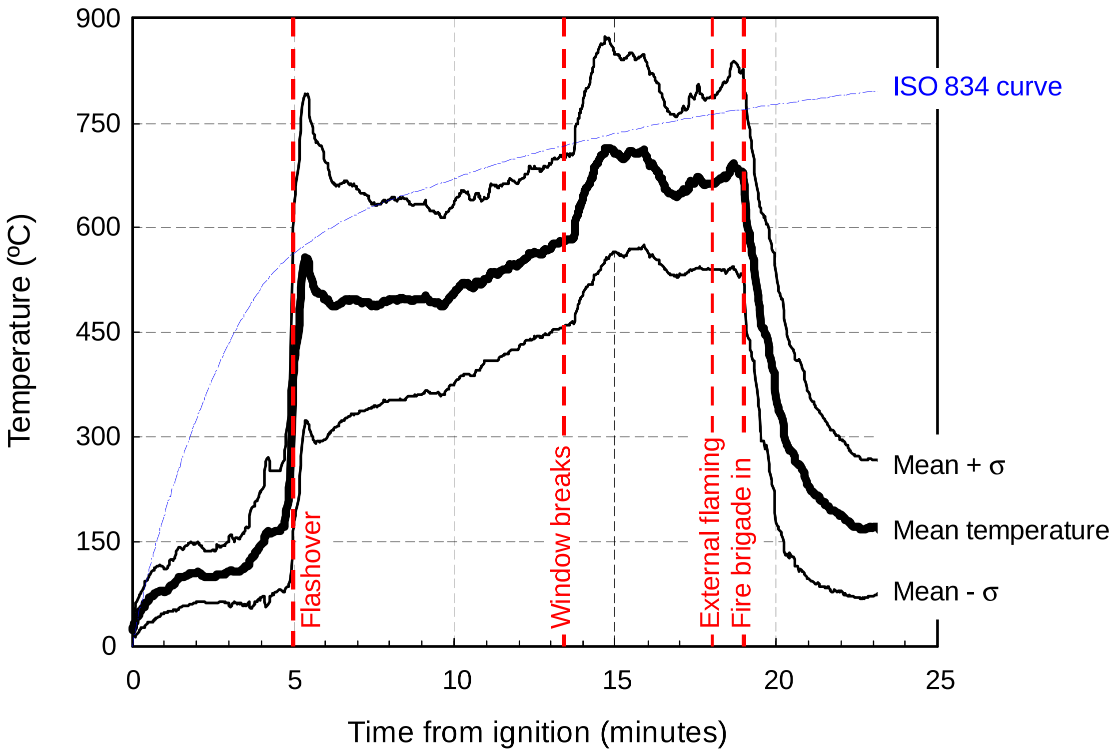

Figure 7: Development of gas phase temperatures in the Test 1 compartment (mean ± 1 standard deviation).

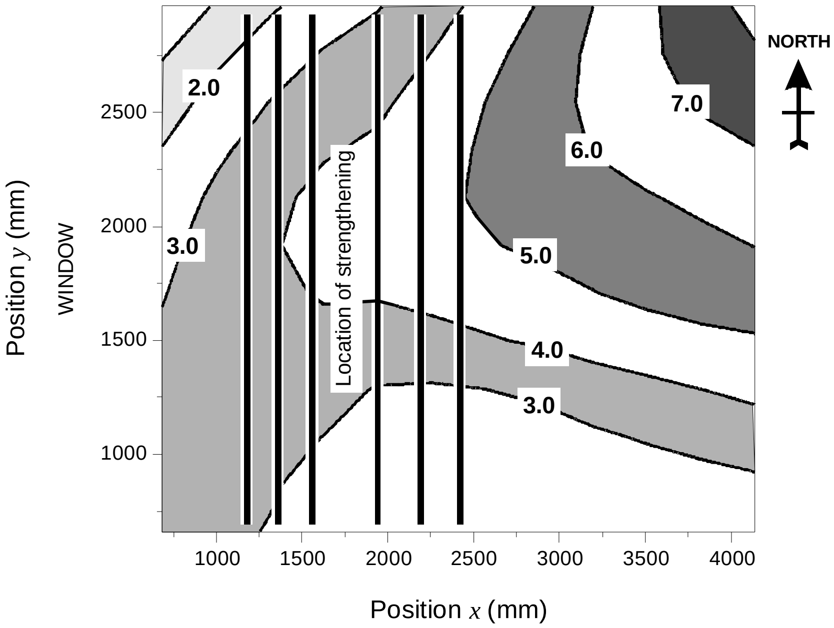

Figure 8: Heat flux incident on the ceiling in the Test 1 compartment (kW/m^2), 4 minutes after ignition.

9(a) Remains of the unprotected plate (Test 1)

9(b) Remains of the intumescent-protected plate (Test 1)

9(c) Gypsum-board-protected plate, protection removed after fire to expose plate (Test 1)

9(d) NSM strengthening after Test 1

9(e) The plate (left) and NSM (right) strengthening after Test 2

Figure 9: The condition of the bonded strengthening after the fire.

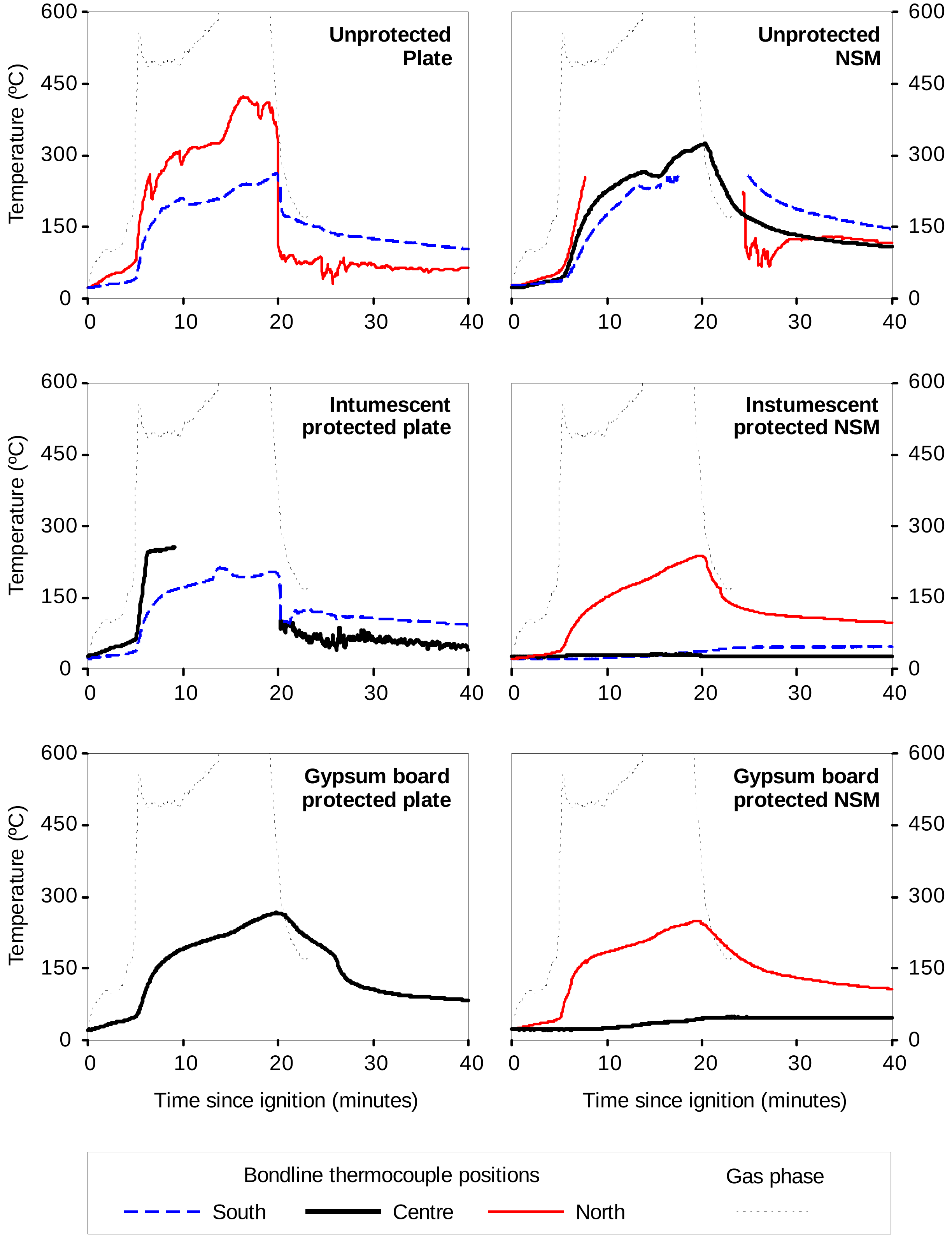

Figure 10: Bondline temperatures.

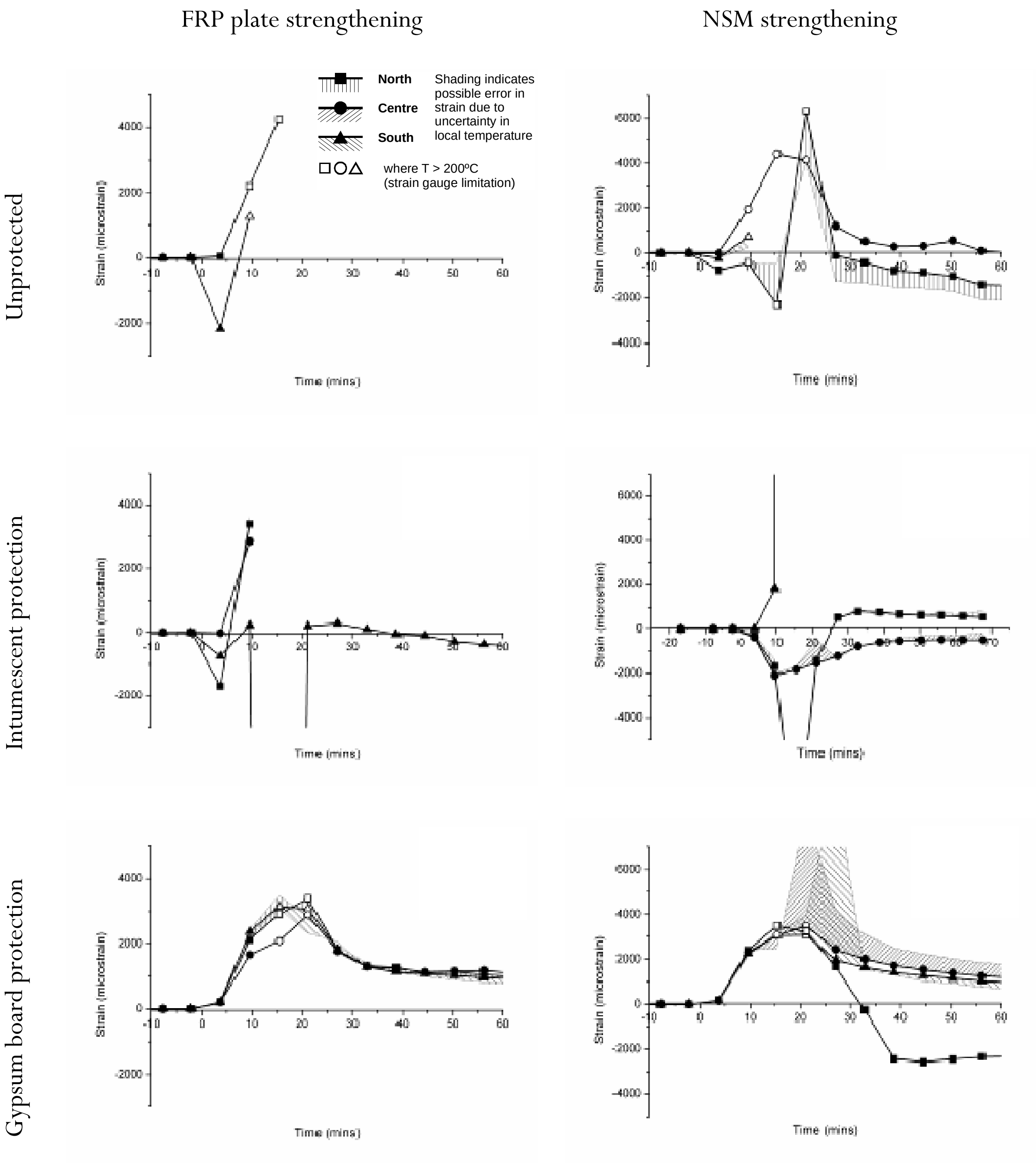

Figure 11: FRP strain measurements.